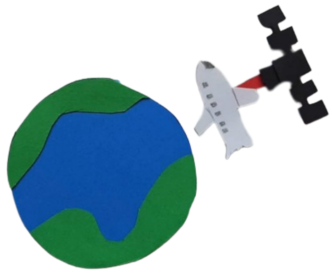
University of California, San Diego

Aircraft Propulsion by Directed Energy Beam Bursts (DEB-B)



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1 Abstract

Directed energy beaming is a promising technology solution for the pursuit of near-zero emissions in the commercial aviation industry by the year 2050. In the context of sustainable aviation, directed energy beaming involves the generation of a high-energy laser at an external power station, utilizing renewable energy sources in the process. The laser is then aimed and beamed to an aircraft in flight, where its energy is used either to activate photovoltaic cells to charge batteries that power propellers, or to power a "laser turbofan," in which the laser energy heats air that is then expelled out of a nozzle to produce thrust. Laser power beaming provides airlines with higher energy density than solar power, 24-hour operational capabilities, and increased payload or lighter aircraft, all while having the capacity to be generated from fully renewable energy sources.

The team proposes the construction of ground-based laser beaming stations along popular domestic flight routes within the next ten to fifteen years, powered with renewable energy sources such as solar, geothermal, or nuclear. Once the viability of the technology has been proven, international government entities can collaborate with private spaceflight and aviation industries to develop and deploy a series of space-based relay and power satellites by the year 2050, thereby significantly increasing the system's range of support. Much of the necessary technology for such a proposal is currently available or in development, although much work remains in terms of guaranteeing operational safety, garnering public acceptance, and securing support from the spacefaring nations of the world. Nevertheless, the team optimistically predicts that the aviation landscape of 2050 would not only support, but thrive under the possibilities offered by laser power beaming technology.

2 Introduction

An article published in a 1979 issue of the journal *Aeronautics and Astronautics* titled “Laser Aircraft” opens with a bold claim:

“A 300-airplane fleet with transcontinental range would save enough kerosene to equal the energy content of the entire system, including power and relay satellites, in one year” [1].

In order to meet the goal of zero-emissions operations by the year 2050, the aviation industry will need to aggressively adapt to a range of innovative, sustainable technologies and practices. In this proposal, the student team at the University of California, San Diego explores how one such novel technology, Aircraft Propulsion by Directed Energy Beam Bursts (DEB-B), could be implemented into the aviation landscape by 2050. The source-to-flight lifecycle, safety concerns, readiness levels, and impacts of the technology from environmental, industrial, financial, and sociopolitical perspectives are discussed.

Laser power beaming is simple conceptually. First, a high-energy beam of light is generated at a power station (which is itself powered by a renewable energy source such as solar, geothermal, or nuclear). The laser is then aimed and beamed to an aircraft mid-flight. The energy contained within this laser provides the sole source of energy for the propulsion of the aircraft. Laser power is proposed over solar as it is more concentrated, can be captured more efficiently than the full spectrum of visible light, and can operate in a wider range of environmental conditions. The team has identified two proposed propulsion methods in this regard: first, the lasers may be directed at photovoltaic cells that charge batteries to power propellers; or second, the laser energy may heat air that is then expelled out of a nozzle to produce thrust (as specified in the competition guidelines, however, the specifics of the storage and use of the energy source once it has reached the aircraft will not be the focus of this proposal).

The team would like to note that throughout this proposal, the terms “laser” and “directed energy” are used interchangeably. The team’s initial concept utilized visible- or near-visible light lasers, but subsequent literature review has indicated the feasibility of using microwave lasers (masers) to achieve similar or better results. This prompted the inclusion of the more general term “directed energy.”

3 Technical Approach and Justification

Despite never receiving mainstream attention, power beaming has long been considered a promising technology by many bright minds in government and industry. Publicly available records proposing laser power as a means of commercial aviation propulsion date back to 1976 [2]. Although some preliminary research was published in the late 1970s and 80s, it was not until 2003 that the first true demonstration of laser-powered flight was performed by NASA engineers at Marshall Space Flight Center. [3] [4]. Since then, various power beaming directives have been funded, mostly in the defense sector, but the technology has been mostly absent from the public eye with regard to commercial aviation [5] [6] [7] [8].

Over 40 years of technological development have occurred since the most in-depth studies on power beaming for commercial aviation purposes were published. The team was motivated to pursue this proposal topic due to both the apparent promise of energy beaming as a near-zero emissions technology, and the lack of recent research focusing on its application in the commercial sector.

3.1 System Overview

US airlines hosted 1 billion passengers on over 10 million flights in 2019 [9]. The demand for air travel is only increasing–it is expected that the annual global number of aviation passengers will reach 9 billion by the year 2050 [10]. Any system intended to replace the fossil fuel propulsion systems powering these flights would need to be massive in scale. The team’s proposed solution would consist of a global array of directed power beaming stations, both ground- and space-based, along with a fleet of aircraft modified to receive power from said stations. The sizing of this system is discussed in Section 4.2 and Appendix A.

The implementation of a power beaming system would consist of three "phases" between the modern day and the year 2050. Each phase represents an increase in scale, cost, and technological challenge and would thus be implemented chronologically. "Phase I" would be a ground-to-aircraft system powered by ground stations, "Phase II" a ground-to-space-to-aircraft system incorporating relay satellites, and "Phase III" a satellite-powered space-to-aircraft system. See Figure 3.a for a graphical depiction.

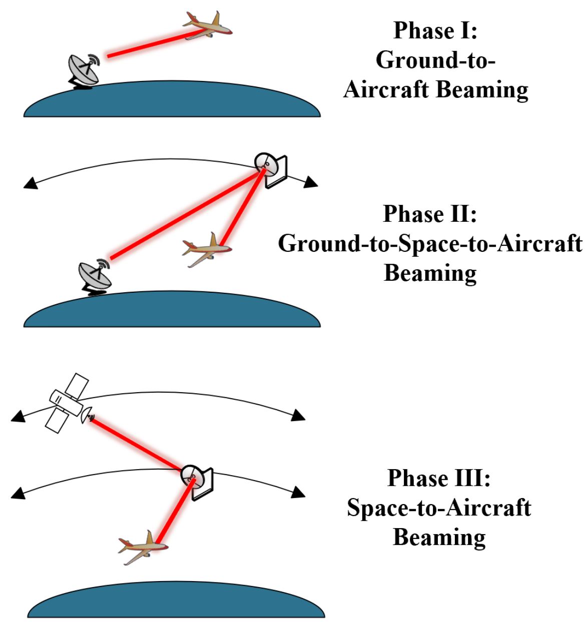

Figure 3.a: A visual representation of the three proposed DEB-B phases.

3.2 Aircraft

One potential design for a laser-powered aircraft involves the use of laser turbofans and receiving dishes. A laser turbofan would consist of typical turbomachinery and a heat exchanger to convert laser energy to thermal energy for the heating of air. Such a device could be incorporated into a traditional kerosene-burning turbofan, allowing it to carry a fuel reserve on which to operate in emergencies. A receiving dish would be mounted onto or incorporated into the aircraft body. Figure 3.b shows two potential designs; one being a modern aircraft retrofitted with a laser turbofan system, the other a novel aircraft design with a receiving dish incorporated into the airframe. Yet another design would be to place the laser receiving dishes directly on the engines. This on-wing concept is the most heavily considered in this paper.

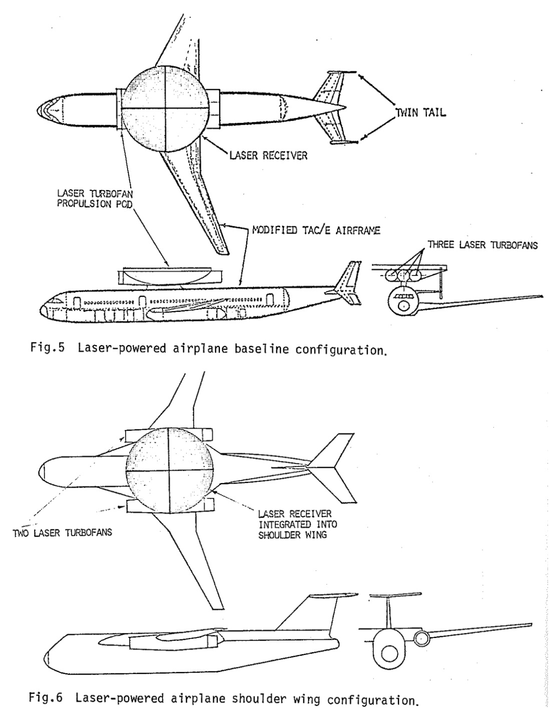

Figure 3.b: Two proposed power beaming aircraft designs from Hertzberg and Sun (1979).

A laser turbofan would consist of typical turbo-machinery and a heat exchanger to convert laser energy to thermal energy. Such a device could reasonably be incorporated into a pre-existing kerosene-burning turbofan. Such laser-powered aircraft would still carry small fuel reserves and maintain their ability to be powered by traditional combustion technology, to be activated only for an emergency landing in case of a tracking failure or loss of the supporting power station. Such redundancy would be prudent until the DEB-B system obtains redundant tracking coverage and is proven reliable beyond a reasonable doubt.

A second design involves beaming energy to photovoltaic cells on the aircraft which charge batteries to power electric propellers.

The ideal laser-powered aircraft would be capable of receiving energy from either ground or space-based stations to avoid the costs of certifying two different designs, one with the receiving hardware atop the aircraft and one with it below. Further analysis would need to be performed to determine viability of a singular design in terms of weight and complexity.

3.3 Takeoff and Landing

Powering aircraft during takeoffs and landings with the DEB-B system pose unique challenges. Depending on the mode of laser-powered propulsion that is implemented, the power sources discussed in following subsections may be inadequate for supplying an aircraft's energy needs during these critical phases of flight; as such, alternative options should be considered. An electrically powered aircraft would not need any special laser beaming requirements during takeoff or landing, as a small onboard battery could provide enough power for that purpose. However, a turbofan engine would require a novel method for beaming energy, especially during takeoff. For this purpose, the team proposes the utilization of a line of lasers embedded in the runway pointing directly up at the engines to provide continuous power as the aircraft lifts off the runway. This line of runway lasers would not need much precision as the aircraft is generally constrained to the runway. They would begin to be built during Phase I, with installations at key airports first. If this system were deemed unfeasible, then runways could instead be outfitted with existing technologies such as Electromagnetic Aircraft Launch System (EMALS) to launch aircraft.

3.4 Phase I: Ground Stations

In Phase I, a series of ground-based power stations, with redundant coverage for safety purposes, would be built along one or more popular air traffic routes (see Appendix A.3 for an example route). Each ground station would consist of an orientable Megawatt laser, receiving and tracking systems, a secondary scanning system (see Section 3.6), and integration with one or more forms of renewable energy. Upon obtaining a secure lock of a target aircraft, the laser would transmit a constant beam of energy to be captured by the aircraft. It would simultaneously receive a stream of data from the aircraft to maintain a successful lock and scan the surrounding air for signs of potential obstructions. When the target aircraft reaches too low of an angle for safe or efficient beaming, the laser would be powered off and the station would be redirected to a new target.

The main limitation of ground stations is their immobility, which limits the range and flexibility of flight paths and makes transoceanic flights practically impossible; as such, it is expected that Phase I would provide coverage only over a select set of popular routes. Their main role would be as a logistical stepping stone to space-based station deployment, proving technological viability while being cheaper to build; restrictions on weight, volume, and dimensions would also be less stringent. Ease of access for maintenance and integration to power sources make their lifecycle effectively unlimited. Another significant consideration is the relative ease of gaining public and political support for a ground-based system before introducing a space-based counterpart. Even after their functionality is replaced by later phases, ground stations could be kept in operation for redundant coverage or to beam power to line-of-sight terrestrial locations.

3.5 Phase II: Relay Satellites

The second step toward developing a power beaming system would be the deployment of a relay satellite network in elliptical orbits. Following a Lockheed design, a beam reaches the satellite and first reflects off of a large flexible receiving mirror [11]. It is then focused toward one or more transfer mirrors which correct any aberrations and provide feedback to the receiving mirror on necessary shape corrections. The beam is then redirected and beamed to its final target. The remaining satellite components include the transmitter structure, control gyroscopes, and fine actuators for the receiving mirror.

By having ground stations beam energy to relay satellites, the range of coverage for target aircraft would be greatly increased, but still limited. The effect on pointing and tracking accuracy due to atmospheric turbulence also becomes a concern. A third evolution of the system is thus warranted.

3.6 Phase III: Power Satellites

The final step in the implementation of a comprehensive power beaming system would be the introduction of space-based power satellites in sun-synchronous orbits consisting of a closed-cycle laser, power generation systems, and necessary optics. Power could be generated with solar-powered thermal engines, photovoltaic cell arrays, or nuclear energy. The use of both relay and power satellites would decrease sizing, cost, and accuracy restrictions compared to a system using solely power satellites [11] [12]. By beaming from orbit to aircraft flying at 10 km or higher, the thickest regions of the atmosphere, and thus the greatest tracking challenges, would be avoided. A proposed design for a power satellite is shown in Figure 3.c.

3.7 Safety

As with any other aeronautical or astronautical endeavor, the deployment of laser beaming technology must be performed with safety as the top priority. Laser technology's most attractive benefit– its ability to produce and transmit concentrated energy at the speed of light– is also its most serious concern from a safety standpoint. Two main questions arise in the discussion of power beaming safety: first, what if the laser beam should accidentally miss its target or have its line of sight obstructed by another object? Second, what if the power stations were hijacked and used as weapons?

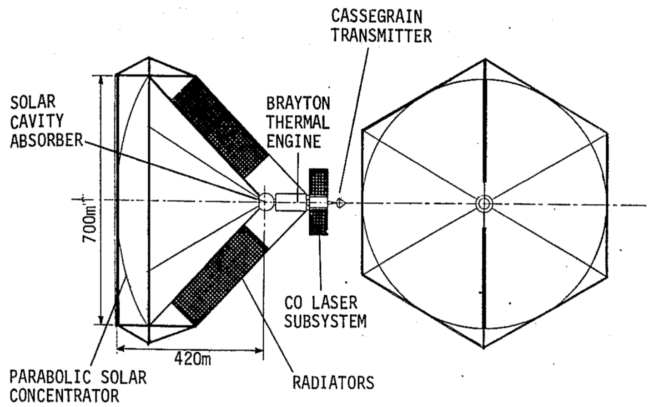

Figure 3.c: A proposed design for a power satellite from Hertzberg and Sun (1979).

Ground- and space-based power stations each introduce their own set of inadvertent targets in the event of an obstruction or tracking failure. For ground stations, the greatest concern is animals and other aircraft. Space-based stations may be obstructed by orbital debris or other satellites; additionally, the risk associated with a tracking failure is greatly increased due to the beam being pointed toward the Earth rather than into the atmosphere. In both cases, there is also a risk of the laser breaching the target aircraft and affecting the passengers and crew.

The second question, regarding the use of directed energy for nefarious purposes, poses a more wide-scale threat. Although nothing resembling a true "laser weapon" has ever been utilized on a battlefield, U.S. military investigation of high-energy laser weapons dates back to the Cold War and continues to the modern day [13] [14] [15]. It will be assumed for the sake of this proposal that DEB-B represents the first deployment of a space-based directed energy device with the capability to harm equipment or personnel.

A rigorous body of technological safety features would need to be integrated into the system to protect against both accidental and intentional misuse of DEB-B. One such feature, as noted by Jin and Zhou, is a secondary Light Detection and Ranging (LIDAR) scanning system "to shut off the system as soon as an animal or aircraft approaches the beam, and then quickly reacquire the target when it is clear." [16] Another crucial system function would be its ability to shut off in the case of any failure to obtain a secure tracking lock on a target aircraft.

Another solution could be opting for a laser configuration that limits maximum terrestrial power propagation levels to within safe margins. The system from Hertzberg et al., for example, would deposit a maximum of around 1 Joule per square centimeter (J/cm^2) to the ground on a clear day, which is below the threshold for skin burns at 6 J/cm^2 [3]. It is, however, above the threshold for retinal burns, although the authors indicate that their system's ability to terminate the laser beam less than 100 milliseconds after a tracking lock failure, along with the improbability of a person looking directly into the beam during perfect optical conditions as it sweeps the ground at approximately 960 kilometers per hour, "[reduce] the probability of eye damage to an infinitesimal level." Such power limitations, however, would be at the expense of the system's ability to provide propulsive energy and might prove too restrictive to be viable.

To complement these safety features, a series of political protocols would also be necessary to guarantee safe operation; this will be discussed in Section 5.4.

4 Aviation Landscape of 2050

As noted in Section 3.1, it is expected that the aviation industry will grow significantly by 2050 as a natural extension of the world's growing interconnectedness. Globalization will continue to drive up both the number of flying passengers and the demand for international freight transport, further instigating the need for eco-friendly flight systems. Between modern day and 2050, changes in the aviation landscape are expected to be driven mainly by cost increases in traditional aviation fuel due to dwindling resources and federal regulations, evolving aircraft designs, and a general increase in public desire for environmentally friendly travel.

Increases in traditional aviation fuel costs are expected to be driven more by federal regulation than by scarcity. Federal incentive programs such as the European Union's "carbon tax" on airlines will likely become commonplace tactics for promoting a shift to zero-emissions operation [17].

The aircraft industry of 2050 is expected to be supported by a US power grid that has been massively upgraded to support the dominance of electric vehicles and other forms of electrification [18]. This includes significant development in nuclear energy, which would be the most promising energy source for ground-based power beaming stations.

Efficiency-driven changes in aircraft form factor are predicted, some of which would integrate especially well with the design changes presented in Section 3.2. One example is the increasingly popular blended wing; the increased surface area would simplify the incorporation of a receiving dish.

4.1 Technology Readiness Levels

The readiness levels of the technologies relevant to a power beaming system vary greatly. In general, the technology related to the high-power directed energy devices would require the most development. Other technologies, such as those contained in the optics and tracking subsystems, are already demonstrated or feasible with modern techniques. Technology, manufacturing, and supply chain readiness levels are discussed below, and summarized in Figure 4.a.

The first technological hurdle facing the implementation of a power beaming system is the development of a sufficiently powerful and compact laser. Any commercial aircraft has a continuous power requirement in the range of tens of megawatts, which no (declassified) laser system outside of laboratories has yet obtained [1]. However, lasers have seen rapid development in their relatively short lifespan. *American Scientist* reports that "the peak power attainable in a laser pulse has increased by roughly a factor of 1,000 every 10 years." [19] Considering that Chinese researchers have already claimed to have developed satellite-deployable directed energy devices with power capabilities of 1-5 Megawatts, it is reasonable to predict that power beaming systems powerful enough to support DEB-B could be produced within the next 10-15 years with sufficient funding and focus [20].

The literature remains divided on the optimal type of laser for power beaming applications. The large body of literature surrounding lasers, along with the field's rapid pace of research, makes it difficult to provide confident speculations as to the state of the technology in 2050 and the most promising lasing medium for power beaming applications. Fiber, diode, solid-state, and free electron laser systems were investigated [16] [21] [22]; for the sake of this proposal, however, the team chose to focus on a laser system inspired by Hertzberg and Sun's analyses of the late 1970s, by far the most technically detailed of their kind [2] [3]. Such a system would be powered by a 40-Megawatt 5-micrometer carbon monoxide (CO) laser (making it a maser, technically, but this proposal will follow the nomenclature of the previous authors). The team has chosen to propose a power beaming subsystem centered on CO lasers for three main reasons: First, the CO laser is an attractive choice in terms of minimizing environmental impact; the reasoning for this will be explained further in Section 5.1. Second, using a laser system of this type would nearly eliminate one of the largest challenges facing other laser systems: propagation efficiency. A laser beamed from the ground to an aircraft or satellite would be partially scattered and absorbed as it propagates through the densest parts of Earth's atmosphere; clouds or other weather effects would further intensify the issue. Efficiency can be maximized by careful selection of electromagnetic wavelengths that propagate most effectively through the atmosphere. Hertzberg and Sun's system, for example, is claimed to obtain a 99% Phase III satellite-to-aircraft atmospheric transmission rate, although Phases I and II beaming would incur greater losses. Third, CO laser technology has been the most analyzed for the subject of power beaming for commercial aviation purposes, thanks to works by Hertzberg and Sun. Their findings have been invaluable in enabling the team to calculate and present rigorous empirical data. It should be noted that literature review and discussion with subject matter experts has indicated that a CO laser is not necessarily the optimal choice for the purpose of long-distance energy beaming, considering for example that CO lasers have developed noticeably less in terms of peak average power and size reduction than other types, such as solid state lasers, in recent years. Nevertheless, the CO laser's benefits make it a promising candidate worthy of further investigation.

Another challenge faced by Phases I and II is tracking and beaming inaccuracy due to turbulence in the atmosphere. Landis and Westerlund indicate that this turbulence typically limits ground-to-satellite tracking and pointing accuracy to around 4 microradians (μrad), an unacceptably large value by at least an order of magnitude [23]. They indicate, however, that a mixture of techniques including a flexible receiving mirror to correct distortions and locating ground stations on mountaintops can significantly mitigate the issue. High-altitude observatory telescopes and ground-to-satellite laser communications systems have already demonstrated accuracies of 0.4 μrad [24]; with this in mind, the team predicts that sufficient accuracy to support ground-to-relay power beaming can be achieved before 2030. Phase III tracking and beaming present fewer issues. The lack of atmosphere in orbit around Earth makes space-to-space laser beaming trivial in comparison; space systems of the 1970s had already reached tracking accuracies of 0.10 to 0.01 microradians [2].

The field of satellite optics has seen incredible development since its inception, with massive increases in resolution and accuracy being accompanied by general decreases in manufacturing cost [25] [26]. The team is confident that the optical developments necessary to enable a power beaming system are already well underway. The greatest challenges lie in designing flexible primary receiving mirrors that can be finely tuned to correct beam aberrations; compacting and lightening the system enough to allow for delivery and orbital insertion; making the subsystems robust enough to survive decades in space; and ensuring that satellites orbit and de-orbit in a safe manner to increase orbital capacity.

Component	2023 TRL	2050 TRL	Justification
Power Generation/ Power Grid	**9**	**9**	Much of this category relies on pre-existing technology and only requires that infrastructure be upgraded, something that will occur concurrently and independently to DEB-B's development.
Laser Power and Efficiency	**5**	**8**	The present understanding of lasers such as CO lasers can be refined through the use of optics and further testing in optimization.
Optics and Receivers	**6**	**9**	The advancement of optics from projects like the James Webb Space Telescope provide a basis with which to apply optical arrays for beaming and tracking from ground stations and satellites.
Manufacturing	**4**	**9**	CO lasers currently have supply chain and manufacturing capability: Scalability is what is needed to ensure a suitable supply is present.
Launch Capability	**6**	**9**	Current launch capabilities are expensive; costs must decrease for the laser satellites to be launched, and this will occur concurrently and independently to the development of DEB-B.
Orbital Capacity	**4**	**8**	Current regulations and technology prohibit spacecraft from orbiting too closely; creating a constellation of satellites requires more work in developing anti-collision measures.

Figure 4.a: Summary of technology, manufacturing, and supply chain Readiness Levels.

4.2 Supply Chain Readiness Levels

The team believes that energy demands, rather than material demands, are most in need of development to support a full-coverage power beaming system by 2050. DEB-B's supply chain needs would vary from phase to phase. Ground stations would see fewer up-front supply chain demands due to their relative ease of construction, but the energy demands over their operational life cycle would be higher. Relay and power satellites may be more energy-intensive to build, but would be self-sufficient once deployed.

The startup cost of ground-based power beaming technology would be drastically lowered if it were able to integrate with pre-existing energy infrastructure. Based on recent federal press releases, regulation regarding renewable energy source conversion, and recent mandates from several states like California on transition to hybrid and electric vehicles in the next thirty years, sufficient infrastructure upgrades are anticipated, at least in the United States [18].

Phases II and III would require orbital insertion, presenting an additional supply chain consideration. Two major supply chain prerequisites are thus sufficient availability of launch vehicles and an overall decrease in kilogram-to-orbit costs, which is currently at around $3300 from the cheapest supplier [27]. NASA has previously cited a goal of tens of dollars per pound by the year 2050, and SpaceX CEO Elon Musk has claimed that Starship launches may eventually reach around $10 per kg, or around $22 per pound [28] [29]. Availability of launch vehicles is not expected to be a major concern, with the number of commercial space launches growing exponentially in recent years and general access to space being greatly expanded [30].

4.3 Manufacturing Readiness Levels

The main challenges of developing a power beaming system are not technology-based; rather, it is the miniaturization of current technology, such as creating smaller lasers and higher efficiency solar cells. Hertzberg and Sun's analyses propose a fleet of 300 aircraft in the air, 400 relay satellites, and 300 power satellites [2] [3]. Bekey, Meyer, and Wolfe propose 200 relay constellations, each composed of 169 mirrors, for a fleet of 2,000 aircraft [1]. Significant developments in the compactness of optical and power generating components are required to decrease production and launch costs and avoid orbital cluttering if such designs are to be implemented for the large airline fleet sizes of 2050.

Current levels of satellite production from private companies such as SpaceX, which builds about 6 satellites a day, imply that Bekey, Meyer, and Wolfe's system could be manufactured in about 15 years if the production facilities were made available [31]. Former analyses placed the lifespans of the power and relay satellites at around 30 years, meaning that today's level of manufacturing is sufficient for full satellite coverage [2], although improvements in materials science and manufacturing processes would likely lead to increased lifespans. Section 5.3 and Appendix A.2 provide further details on sizing.

4.4 Projected Timeline

A preliminary timeline for the implementation of the DEB-B system is shown in Figure 4.b below.

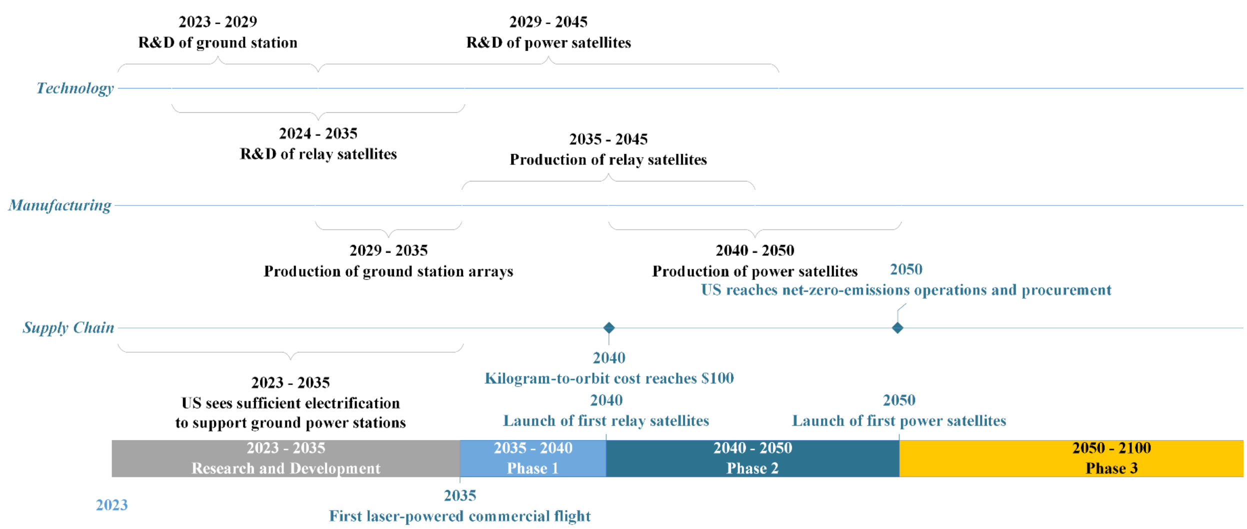

Figure 4.b: Projected timeline of technology, manufacturing, and supply chain development.

5 Technological Impact

The introduction of a system as complex and transformative as DEB-B would likely produce impacts that reach far beyond the sphere of commercial aviation. As such, a multifaceted approach is necessary to consider and address the associated concerns and ensure that such a system could be realistically and equitably implemented.

5.1 Environmental

DEB-B has the potential to greatly decarbonize air travel operations. Aviation CO_2 emissions contributed around 2.4% of total global emissions in 2018 [32]. While this number is relatively small, releasing emissions at higher altitudes multiplies their effects. In 2021, the US transportation sector was nearly entirely petroleum-based [33]. DEB-B would shift the energy production away from carbon-intensive fuels towards sustainable electricity generation to reduce emissions, especially those produced at altitude.

Current aircraft produce about 70 to 95 grams of CO_2 per passenger kilometer (pkm) [34]. The worst case for DEB-B aircraft is assumed for this analysis, that aircraft in 2050 are only equally energy efficient in aerodynamics and propulsion, and that electrical energy generation is equally carbon-intensive in 2050 as it is today. The Phase I DEB-B system, with ground stations from LAX to SEA, would reduce CO_2 emissions by 15% to 37% if calculated using current California electricity generation emissions. This means that even if implemented without any other carbon neutrality objectives reached by 2050, DEB-B would have a significant positive impact on the carbon emissions produced by the aerospace industry. Even so, the Phase III system eliminates even this shortcoming as it utilizes solar power in its satellites and therefore has zero emissions from power generation. Rocket launches of power and relay satellites become the main emissions generator, reducing CO_2 emissions of the entire system by over 99%! Appendix A.5 provides calculations for this claim.

Although the transition to energy-beamed propulsion signifies a massive step away from the burning of fossil fuels, the technology would not be free of environmental impact. The manufacturing of the power stations, especially the laser subsystem itself, is a significant environmental concern. As noted, there exist a variety of laser subsystems that could be used for power beaming, introducing a range of constituent materials varying in rarity, cost, and environmental impact. The CO laser chosen for this analysis is attractive in this sense, with its lasing medium being composed of relatively abundant gasses [35]. The rarest and most energy-intensive component of a CO laser is the helium that is used as a filler material. CO lasers' high efficiency also allows them to offer power savings over other types of lasers. The environmental impact of other components of the CO laser subsystem, such as the pump, optics, and structural materials can be mitigated utilizing sustainable manufacturing processes; specific analyses would need to be performed to investigate whether the large scale of the system would lead to disproportionately large environmental impacts during the manufacturing and construction stages. As previously noted, the team's choice to investigate CO lasers as opposed to other types of lasers was motivated partially by the CO laser's inability to ionize the atmospheric air that it propagates through, which is a potential environmental concern facing other types of lasers. Supporting calculations are shown in Appendix A.4. Furthemore, a maser, compared to a visible light laser, would have less likelihood of disrupting the view of the night sky.

Depending on their location, size, and mode of operation, ground stations could have considerable impact on their immediate surroundings. One or multiple ground stations could be placed at participating airports if their presence is deemed safe and sufficient space is allocated. Intermediary ground stations, however, would be most effectively placed at high altitudes and far from densely populated areas. Besides the potential habitat destruction and disruption during their construction, the operation of the ground stations also presents the possibility of more long-term ecosystem disruption in their immediate vicinities, similar to the localized effects that have been researched around solar farms and nuclear power plants [36] [37]. These effects could be mitigated by careful selection and responsible operation of ground station locations. Overall impact is also limited in the sense that, as noted in Section 3.4, it is expected that only a relatively small number of ground stations will be constructed overall.

Space-based stations would need to include more energy-intensive structural elements. They would also require solar cells, likely composed of a gallium arsenide derivative as is common in space applications. Each of these subsystems carries with it the environmental impact necessary to source, refine, and integrate its components.

5.2 Industrial

Whether of its own volition or under regulatory pressure, the aviation industry will be required to adapt to advancements in energy technology. General aircraft manufacturing procedures would need to be altered to account for the new propulsion subsystem, be it photovoltaic cells and propellers or receiving dishes and laser turbofans. Airports, fortunately, would not need to alter much of their operational structure to accommodate changes in aircraft. One of the largest changes would involve the manufacturing, operation, and maintenance of power stations over popular routes of aircraft travel. Pilots and air traffic controllers would need to be trained to operate safely with the new power beaming infrastructure. During Phase I, it may be warranted or even required to fly aircraft at lower altitudes to avoid propagation losses or cloud cover; noise and efficiency analyses would need to be performed. Changes in air traffic routes might also be implemented to accommodate ground station placement. These changes would likely be small in scale given the limited scale of Phase I. Aircraft powered by Phases II and III might benefit from flying higher than modern aircraft due to reduction of drag and beaming efficiency losses.

DEB-B's implementation would likely require cooperation between government agencies and the private aviation industry on a scale not yet seen. This is due to both the large capital investment required and the necessity for regulation on a public level for safety, security, and sociopolitical reasons. This cooperation might take on a form similar to NASA and Boeing's recent Sustainable Flight Demonstrator project, with private industry and public entities working together to research and deploy the DEB-B system [38]. In the long term, DEB-B's potential to provide power to a diverse range of commercial, private, and military aircraft, both piloted and unpiloted, may usher in design changes across other fields of the aerospace industry as companies and agencies work to integrate this transformative energy source.

5.3 Financial

The largest financial hurdle to implementing DEB-B is the capital cost of manufacturing and launching space-based power stations and relays. Various methods of organization for the financial operation of the system can be imagined; for the purposes of this report, the team proposes a system similar to that described by power beaming pioneer Leik Myrabo, in which "laser (or microwave) energy [is] sold by satellite power station consortiums to the [aerospace] industry on a contract basis." [22] The team recommends that one or more non-airline companies build and sell power from these satellites as a service. The cost to build and launch each satellite is estimated to be $11.2 million at most. See Appendix A.2 for calculation details. Given 30 years of development and manufacturing at scale as shown in the development timeline above, this price point is feasible to achieve. The companies owning the satellite infrastructure can also sell their service to power rural energy networks, other satellites, emergency services, and potentially off-world mining companies for a greater return on investment. Hertzberg et al. provide another excellent, albeit dated, cost analysis [3]; decreases in manufacturing and launch costs would need to be considered in a contemporary analysis.

5.4 Social and Political

A significant challenge to implementing orbiting power beaming stations would be political and social backlash. On the political side is a history of superpowers clashing over the use of laser weapons in space [39]; on the social side is the perception of lasers as deadly weapons in science fiction and pop culture. DEB-B's deployment would likely be preceded by international agreements banning the use of laser weaponry in space; without them, the satellites would be viewed as military targets. Such agreements could build upon pre-existing protocols for the use of lasers, but much more diplomatic work remains to ensure safe operation [40] [41]. Even if private ownership is found to be more efficient or cost-effective, satellites may need to be operated or regulated by public entities, perhaps even as an international collaboration to address security concerns. In addition, current regulation of satellite orbits and de-orbiting create a regulatory hurdle, as the sheer number of satellites required to keep DEB-B operational would constitute risking satellite collision and debris. Care must be taken to ensure safety in the satellite design to satisfy current and future regulations.

Social and political acceptance of DEB-B could be aided by its potential application for non-aviation purposes such as emergency power beaming to places affected by natural disasters– only a shipping crate with a large photovoltaic receiver would need to be shipped to the affected area. Beyond 2050, space-based power beaming might make up a significant portion of the energy infrastructure of terrestrial and even lunar society.

6 Documentation of Research Development and Changes

As requested in the competition guidelines, the following section documents the changes between the initial proposal, submitted on February 28th, 2023, and this final research paper. The majority of the changes were elaborations on existing sections. A new subsection was also added, motivated by judges' feedback.

Additional historical background was added to Sections 2 and 3 to provide useful context and improve the narrative structure of the paper.

Further detail on the engineering and operation of laser-powered aircraft was added to Section 3.2 to elaborate on the subsystem and the feasibility of its production and integration with modern or near-future technology. This included drawings of potential laser-powered aircraft and power station designs were added to Sections 3.2 and 3.6, respectively, to complement the written descriptions of the subsystems.

Following judges' feedback, Section 3.3, "Takeoff and Landing," was researched and added to address the unique power beaming challenges faced during these stages of flight.

Additional justification of the team's choice of laser subsystem was added Section 4.1 to expand upon the merits of CO lasers while emphasizing the possibility of alternate options.

An introductory paragraph was added to the beginning of Section 5 to emphasize the multifaceted nature of the proposal's impacts, including its use outside of commercial aviation.

Additional literature review, calculation, and speculation was performed regarding various aspects of DEB-B's environmental impact, including overall carbon emissions of the entire system; the system's potential to cause adverse environmental effects by way of ionization of atmospheric air; and the impacts of ground stations on their immediate surroundings. The team's findings were incorporated into Section 5.1 and Appendix A.

Additional information was added to Sections 5.3 and 5.4 to discuss whether public or private entities would take responsibility for the manufacturing and operation of space-based power and relay satellites.

The concluding paragraph in Section 7 was lengthened to include a summary of the contents of the final research paper.

7 Conclusion

In this proposal, the student team at the University of California, San Diego introduced a fully-fledged energy beaming system for aircraft propulsion, with a proposed implementation by way of a three-phase process incorporating ground-based power stations followed by space-based relay and power satellites. The readiness levels for such a system were examined in terms of technology, manufacturing, and supply chain. Finally, the potential impacts of the system were considered from environmental, industrial, financial, and sociopolitical perspectives. Offering over 99% reduction in carbon emissions and high versatility in use cases, directed energy power systems such as DEB-B present a viable path to a clean, efficient aviation landscape by 2050.

Appendix A – Calculations

A.1 Friis Transmission Equation

The Friis transmission equation describes power transfer between a transmitter and a receiver:

$$P_R = P_T \frac{A_R A_T}{r^2 \lambda^2}$$

where P_R is the power received,

P_T is the power transmitted,

A_R and A_T are the areas of the receiver and transmitter dishes, respectfully,

r is the distance between the receiver and transmitter,

λ is the wavelength of the directed energy beam.

It can thus be seen that the power received by a laser aircraft could be maximized by

- Maximizing transmitted power, which is limited by energy supply and technological barriers; however, considerable growth in the maximum average power of directed energy devices has been observed since their invention.
- Maximizing aperture size. For an aircraft, this is limited by aerodynamic and structural loads. For a satellite, cost and sizing for launch and orbital deployment capability is the main limiting factor. For a ground station there are fewer restrictions and apertures could be as large as feasible to manufacture.
- Minimizing distance between the receiver and transmitter, which is possible in limited scopes. Aircraft can fly lower to be closer to ground stations until the point that either noise reaches the ground or efficiency losses due to increased drag reach unacceptable levels. Aircraft can fly higher to be closer to relay satellites until the air is too thin to allow for sufficient production of thrust.
- Minimizing the wavelength of the beamed energy. In this sense, higher wavelengths are advantageous. However, lower wavelengths are advantageous in that they can penetrate cloud cover and reduce energy losses during atmospheric propagation.

A.2 Financial Break-Even Cost Per Satellite

The break-even cost of a single relay satellite (from design to orbit) is estimated below compared to the current cost of jet fuel used in 2018 dollars.

In 2018, airlines flew 8.5 trillion revenue passenger kilometers (RPK), using about 3.5 liters of fuel per 100 RPK, resulting in 238 billion liters of fuel worth roughly $150 billion (at just over $0.60 per liter), with over 9500 planes in flight on average [34] [42] [43].

Using the previously established 30 year satellite lifespan, and with the number of relay mirrors provided in Bekey, Meyer, and Wolfe, the break-even cost per relay satellite to keep a similar number of planes in-flight is $11.2 million. Each global set of relay satellites contains 169 satellites, and conservatively assuming each set can only support four planes at a time, about 2375 sets are required. That's 401,375 satellites! Each satellite, over its 30 year lifespan, would be relaying power with little upkeep needed. If all $150 billion of fuel per year was used to buy satellites, over 30 years (to keep a rotating cast of 401,375 satellites up to date), the world would be building and launching 13,380 satellites per year at a cost of about $11.2 million per satellite.

A.3 Ground Station Placement

For demonstration purposes, the first ground-based power beaming route would be best placed in a low-risk environment– for example, powering cargo vehicles in a sparsely-populated area. Once the system's effectiveness and safety has been proven, subsequent ground-based power beaming arrays would ideally be built along short, popular routes in order to achieve high utilization rates to offset costs. Los Angeles (LAX) – Seattle (SEA), for example, would be an excellent route, hosting an average of 2,400 flights per month. Based on simple calculations from variables found in Figure A.3.a, with an aircraft cruising altitude of 30,000 ft, such a route would require approximately 7 ground stations, including 2 at each airport.

The number of required ground stations can be calculated based on aircraft cruising altitude and the ground station transmitters' minimum deflection angle. The number of ground stations can be calculated as such:

$$\#\,Ground\ Stations\ = ceil\left(\frac{\theta}{2\cdot[180+\frac{\phi}{2}-arcsin(R_e\cdot\ sin(180+\frac{\phi}{2})/(R_e+h)]}\right)+1$$

Where θ is the angle of the great circle arc between two airports,

ϕ is the ground stations' transmitter deflection angle range,

R_e is the radius of a spherical Earth,

h is the cruising altitude of the aircraft.

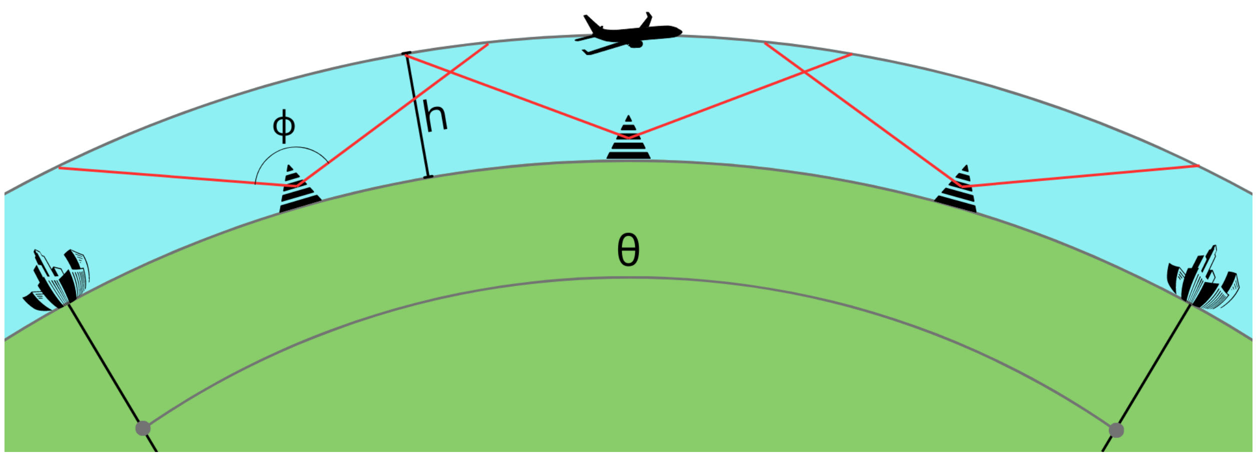

Figure A.3.a: Ground station spacing variables for a point-to-point route.

A.4 Ionization Calculations

Based on the wavelength of the laser, in this case 5 micrometers, the frequency of the wave can be calculated. The energy of the wave is then found using Planck's equation.

$$f\ =\ \frac{V}{\lambda}=\ \frac{3\times10^{8}}{5\times10^{-6}}=\ 6\ \times\ 10^{13}Hz$$

Where f is the frequency of the wave,

V is the velocity of the wave which is the speed of light,

λ is the wavelength.

Planck's Equation: $E = h \times f = (4.136 \times 10^{-15}\, eV \cdot s) \times (6 \times 10^{13}\, Hz) = 0.248\, eV$
Where E is the energy of the wave,
h is Planck's constant in electron volts · seconds,
f is the frequency of the wave.

Note, the air is primarily composed of Nitrogen and Oxygen gas. Of the two, Oxygen gas has the lowest ionization energy of around 13.6 eV. This means that the laser is under the ionization energy of the air by a factor of around 54.8. Furthermore, these calculations are under the assumption that 100% of the energy will be lost to the atmosphere. However, the energy loss of a 5 micrometer maser is around 1%. Therefore, the laser is under the ionization energy of air by a true factor of around 5483.

A.5 Carbon Footprint Calculations and Comparisons

Current aircraft consume about 2.94 liters of fuel per 100 passenger kilometers (that's 0.0294 L/pkm, or 23.52 g/pkm of fuel) [44], and emit 70 to 95 g/pkm of CO_2 [34]. Fuel energy density hovers around 12 Wh/g [45]. Multiplying the two values results in energy density required per pkm, a value of 282.2 Wh/pkm. This analysis assumes that future aircraft are only just as energy efficient as current 2023 aircraft, such that they also consume an equivalent 282.2 Wh/pkm. DEB-B Phase I and Phase III total emissions are now considered.

For Phase I:

Considering that DEB-B aircraft would not have to carry fuel, a 40% reduction in weight is achievable on the Boeing 787 (therefore the DEB-B aircraft would be 60% the weight of current aircraft) [46]. Power for the Phase I DEB-B craft would come from the electrical grid, with the efficiency of the laser power station calculated to 50% [16]. As Phase I is set to be a demonstrator route from LAX to SEA, current emissions for California electric generation are used at 391 lbs of CO_2 per MWh generated (0.177 g/Wh) [47], which assumes no improvement in carbon efficiency to 2050 (a worst case scenario). Therefore the amount of energy generation required to power an equally-efficient aircraft with a Phase I ground-based laser is $282.2 \times 60\% \div 50\% = 338.7$ Wh/pkm, generating 60 grams of CO_2 per pkm. This is a 15% to 37% reduction in emissions from the given 70 to 95 g/pkm CO_2 of current aircraft.

For Phase III:

The largest source of emissions will be rocket launches to launch all the relay satellites into space, as all of the actual power generation will be from renewable sources in space, mostly solar. From Appendix A.2, it is known that roughly 13,380 satellites are replaced/launched each year. Once again using worst case scenarios, each satellite requires its own spacecraft (a Falcon 9) to launch, and spacecraft do not become any more efficient by 2050, meaning that each Falcon 9 launch creates 425 metric tons of CO_2 (425,000,000 grams) [48] [49]. That adds up to 5.69 trillion grams of CO_2 per year. However, divided by the 8.5 trillion passenger kilometers flown in 2018 [34], each passenger kilometer only emits 0.669 grams of CO_2, an over 99% reduction in carbon dioxide emissions from current fuel-burning aircraft.

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